Preparing for the quagga mussel (*Dreissena rostriformis bugensis*) in Great Britain

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Summary

The quagga mussel (*Dreisena rostriformis bugensis*) is a highly invasive non-native freshwater species from the Ponto-Caspian region. A risk assessment for this species has identified it is very likely to enter and establish in Great Britain in the near future, with major impacts to ecosystems and a range of economic interests. The impacts are likened to those of zebra mussel (*Dreisena polymorpha*), but are potentially worse due to wider habitat tolerance. Quagga mussel is not yet present in Great Britain. This project is intended to provide guidance on potential management, if any, that could be used to respond rapidly to this species should it be found in GB waters.

Quagga mussels are a relatively new invader to western Europe and North America compared with the zebra mussel. The two species share the same native range and their tolerance of environmental stressors are broadly similar. This means that the considerable literature on zebra mussel management is also of value in identifying the most appropriate responses to quagga mussels. However, there are some distinct differences between the two species, which are highlighted in the report where relevant and where known.

The most likely option for eradication in a small, isolated water body is to dewater and to treat any remaining standing pockets of water with a biocide such as copper sulphate. Eradication in a large isolated water body is more challenging, but targeted application of biocides and induction of oxygen stress is possible through the use of plastic sheeting upon the hard substrates to which the mussels attach. In waters destined for potable supply the most viable options are likely to allow for containment rather than eradication. These include introduction of molluscivorous fishes, removal of mussels by SCUBA and the use of biocides approved for use in potable waters (BioBullets).

Eradicating quagga mussels in flowing waters is unlikely to be possible. They will not establish in shallow streams, and large rivers would require considerable volumes of water to be treated with a control agent. Moreover, if quagga mussels establish in river, it is likely that the species will distribute widely through the system and so an eradication attempt is likely to be unviable. If quagga mussels are found in a canal, it may be possible to isolate the fouled section and treat it as an isolated small water body. If quagga mussels are found within the lower reaches of a river, it may be possible to reduce flow to encourage a tidal saline increase (>4 ppt) to kill the quagga mussels. Quagga mussels are relatively intolerant of saline waters, and so control strategies recommended for freshwaters will be equally effective in brackish waters.
Many interventions will require regulatory approvals. These are reviewed in detail, and an estimate given for the time required to obtain the necessary consents. Regulations of particular importance include the EU Biocides Regulation (Regulation 528/2012), the Water Resources Act 1991 (as amended by the Environment Act 1995), Natural England’s permit or Appropriate Agreement, and for potable supplies the Water Supply (Water Quality) Regulations 2000.

The report reviews the likelihood of the existing Check, Clean, Dry initiative in serving as an effective biosecurity measure. It is concluded that the approach will be broadly effective, although suggestions are made on the appropriate periods of drying and the use of hot water. It is also considered that additional biosecurity measures should be employed for the removal of structures from a fouled waterbody that have been standing for a prolonged period and may therefore have become fouled by well-attached mussels.
1. Introduction

In recent years, there has been a dramatic spread of Ponto-Caspian species into Western Europe (Bij de Vaate et al, 2002). This spread has been facilitated by the construction of canals which have linked different river systems. Many of these new species have driven major ecological changes and caused considerable economic harm. Recent studies suggest that The Netherlands contains over 20 Ponto-Caspian species that have yet to be found in Great Britain (Gallardo & Aldridge, 2013).

One of the Ponto-Caspian species of greatest concern to Britain’s freshwaters is the quagga mussel, *Dreissena rostriformis bugensis* (Andrusov, 1897), which is expected to be discovered in the very near future (Aldridge, 2012). Until the early twenty-first century the quagga mussel was a slower invader than the zebra mussel *Dreissena polymorpha* (Pallas, 1771), a species that already costs Britain approximately £5m (Oreska & Aldridge, 2011) and threatens our native biota (Aldridge et al., 2004; Sousa et al., 2011). The original native range of the quagga mussel is the Lower Dnieper River and Southern Bug River (Son 2007). However, over the last few decades the quagga mussel has considerably extended its range, establishing widely in Russia, North America and Western Europe (van der Velde et al., 2007).

The only species with which quagga mussels will directly compete in Britain is the zebra mussel. Throughout its invaded range, quagga mussels have been seen to replace zebra mussels in most habitats (Wilson et al., 2006; van der Velde et al, 2010). This has been attributed to the lower respiration rates, greater shell growth, greater shell mass, faster filtration rates and greater assimilation efficiency (Diggins, 2001; Baldwin et al., 2002; Stoeckmann, 2003). Zebra mussels appear to find refugia from quagga mussels in certain habitats, including those with fast flow, and areas with macrophyte substrate onto which zebra mussels preferentially attach (Diggins et al., 2004). In The Netherlands, quagga mussels take approximately four years after discovery to dominate over zebra mussels (D. Platvoet, personal communication). In Russia, this lag is estimated to be 5-10 years (Orlova et al., 2005).

Quagga mussels will affect invaded ecosystems in a number of ways. Clearer waters resulting from massive filtration capacity (Cross et al., 2010) will lead to changes in algal diversity and abundance. Selective removal of green algae by dreissenids can reduce cyanobacteria from competition and lead to toxic blooms (MacIsaac et al., 1996). Grazing of algae by quagga mussels was estimated to match
that of zooplankton in Lake Erie, USA (Zhang et al., 2010) and may explain the significant declines in biomass of cyclopoid copepods in Lake Ontario following mussel invasion (Bowen et al., 2011). The abundance of ciliates, *Daphnia* and rotifers reduced by 39, 40 and 45% respectively in Lake Michigan following dreissenid invasion (Kissman et al., 2010).

Nalepa et al. (2009) found that offshore benthic communities in Lake Michigan experienced a major shift following the invasion of quagga mussels, with the replacement of native amphipods with the new mussel. A meta-analysis of benthic macroinvertebrate communities following *Dreissena* invasions (Ward & Ricardi, 2007) suggests that following invasion, there is an increase in benthic density and taxonomic richness, but a reduced evenness. There were positive effects on densities of scrapers and predators (especially leeches, flatworms and mayflies), but reductions in large snails, spaeriid clams, unionid mussels and burrowing amphipods. Gammarid amphipods showed a positive response. A decline in unionid mussels through quagga mussel fouling has been reported by Schloesser et al (2006). This is likely to pose a threat to Britain’s threatened mussel *Pseudanodonta complanata* (Sousa et al., 2011), a UK Biodiversity Action Plan Priority Species.

Bioclimatic models suggest there is wide habitat suitability within Great Britain for quagga mussels to establish (Fig. 1). As a rule of thumb, it can be assumed that the widespread distribution of Zebra mussels in GB will be similarly matched by quagga mussels, which will replace the Zebra mussels in many sites. Distribution is likely to include much of England, western and southern Wales and central Scotland. Quagga mussels favour lentic systems, such as reservoirs and lakes. They are not found in fast flowing rivers, but canals provide ideal habitats. British freshwaters provide a wealth of suitable hard substrates which has already been seen to support the widespread establishment of zebra mussels. As populations establish, shell material enables expansion into muddy substrates (Bially & MacIsaac, 2000).

Quagga and zebra mussels are also prolific biofoulers in industries that use raw water. The combined effect of these species on North American electric generation and water treatment facilities between 1989 and 2004 is estimated to be $US267 million (Connelly et al, 2007). Zebra mussel management in GB is estimated to cost approximately £5m per year (Oreska & Aldridge, 2010).

Given the potential ecological and economic impacts that quagga mussels could have in Britain’s freshwaters, it is desirable to develop an action plan to manage the threat. Ideally, a pathway management plan would be developed, which could help to identify vectors and pathways by which the species may reach Britain. High risk vectors and pathways could then be managed appropriately.
Unfortunately, we currently do not have such a pathway management plan developed for any potential freshwater invaders into Great Britain.

Figure 1. Estimated optimal habitat range for the quagga mussel in the United Kingdom. Predictions are based on bioclimatic models (Gallardo & Aldridge, 2013).

As a second tier of defence, it is therefore prudent to establish monitoring programmes which can maximise the chance of early detection. As Figure 1 shows, the wide potential distribution of quagga mussels in Britain makes it challenging to focus monitoring efforts spatially, although it is notable that many recent freshwater invaders in Britain have first established in eastern England. The GBNNSS has developed Fact Sheets and a Species Alert to encourage early detection and reporting, and the Environment Agency and water industry has been encouraged to look out for the species during routine work.

Assuming existing measures result in an early detection, and if subsequent rapid surveys show the population to be relatively contained, it may be possible to attempt the eradication of the population. In order to allow an immediate, fully-informed eradication attempt, it is necessary to have developed an action plan which is appropriately costed and readily funded. This report aims to
facilitate the production of a suitable action plan by reviewing the control options available and considering their suitability for eradicating quagga mussels in different scenarios under which the species might be found (small isolated water body, large isolated water body, isolated water body used for drinking water, flowing water, brackish water).

Even if a population cannot be realistically eradicated, it is still desirable to contain populations to minimise the economic and ecological consequences of further spread. Such containment requires the development of suitable biosecurity measures. This report therefore also considers the suitability of existing measures (Check, Clean, Dry) and identifies additional measures that could be used to further reduce the risk of spread.
2. Quagga mussels and zebra mussels: similarities and differences

Compared with quagga mussels, zebra mussels have had a much longer invasion history within Europe and North America. This means that a much greater amount of literature has focused on control options for zebra mussels. It is therefore pertinent to consider to what extent the ecology and environmental tolerances of the two species are similar or different, as this will inform on the confidence with which we can extrapolate across species.

Both species share a similar native range, which means that their broad environmental tolerances and habitat requirements are similar. This is reflected in the detailed synthesis of the literature by Mackie & Claudi (2010; Tables 1 and 2).

Table 1. Potential for population expansion of the zebra mussel in waters of varying chemistry. Data are based on North American experiences (adapted from Mackie & Claudi, 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No survival</th>
<th>Poor growth</th>
<th>Moderate growth</th>
<th>Good growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (mg Ca/l)</td>
<td>&lt;8</td>
<td>8-15</td>
<td>&gt;15-30</td>
<td>&gt;30</td>
</tr>
<tr>
<td>pH</td>
<td>&lt;7.0, &gt;9.5</td>
<td>7.0-7.8, 9.1-9.5</td>
<td>7.9-8.1, 8.9-9.0</td>
<td>8.2-8.8</td>
</tr>
<tr>
<td>Alkalinity, total (mg CaCO₃/l)</td>
<td>&lt;30</td>
<td>30-55</td>
<td>56-100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/l)</td>
<td>&lt;3</td>
<td>3-6</td>
<td>7-8</td>
<td>&gt;8</td>
</tr>
<tr>
<td>Chlorophyll a (mg/l)</td>
<td>&lt;2, &gt;25</td>
<td>2-2.5, 20-25</td>
<td>&gt;8 - &lt;20</td>
<td>&gt;2.5 - 8</td>
</tr>
<tr>
<td>Temperature (˚C)</td>
<td>&lt;10, &gt;32</td>
<td>26-32</td>
<td>10-20</td>
<td>&gt;20 - &lt;26</td>
</tr>
<tr>
<td>Salinity (ppt)</td>
<td>&gt;10</td>
<td>&gt;8 -10</td>
<td>5-8</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

Table 2. Potential for population expansion of the quagga mussel in waters of varying chemistry. Data are based on North American experiences (adapted from Mackie & Claudi, 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No survival</th>
<th>Poor growth</th>
<th>Moderate growth</th>
<th>Good growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (mg Ca/l)</td>
<td>&lt;10</td>
<td>10-12</td>
<td>&gt;12-30</td>
<td>&gt;30</td>
</tr>
<tr>
<td>pH</td>
<td>&lt;7.0, &gt;9.5</td>
<td>7.0-7.8, 9.1-9.5</td>
<td>7.9-8.1, 8.9-9.0</td>
<td>8.2-8.8</td>
</tr>
<tr>
<td>Alkalinity, total (mg CaCO₃/l)</td>
<td>&lt;35</td>
<td>35-42</td>
<td>&gt;42-100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/l)</td>
<td>&lt;4</td>
<td>4 - 6</td>
<td>7 - 8</td>
<td>&gt;8</td>
</tr>
<tr>
<td>Chlorophyll a (mg/l)</td>
<td>&lt;2, &gt;25</td>
<td>2-2.5, 20-25</td>
<td>&gt;8 - &lt;20</td>
<td>&gt;2.5 - 8</td>
</tr>
<tr>
<td>Temperature (˚C)</td>
<td>&lt;2, &gt;30</td>
<td>2-10, &gt;28-30</td>
<td>&gt;10-16, &gt;24-28</td>
<td>&gt;16-24</td>
</tr>
<tr>
<td>Salinity (ppt)</td>
<td>&gt;10</td>
<td>&gt;8 -10</td>
<td>5-8</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>
While most assessments of the environmental requirements and physiological tolerances of quagga mussels are based on zebra mussel criteria, there are some exceptions. These exceptions are reviewed briefly below to illustrate that some control methods that have proven effective for zebra mussels may require modification in order to be suitable for quagga mussel control.

**Calcium:** Quagga mussels appear to have a higher calcium threshold than zebra mussels for settlement and growth. Jones & Ricciardi (2005) found quagga mussels in the St. Lawrence River at sites with a calcium concentration of 12.4-30.0 mg/l, while zebra mussels occupied sites as low as 8 mg/l.

**Dissolved oxygen:** Quagga mussels can tolerate lower dissolved oxygen levels than zebra mussels. Karatayev et al. (2007) suggest that quagga mussels need >1.5 mg/l of oxygen at 20°C, while zebra mussels need >3.0 mg/l (Mackie & Claudi, 2010). This might explain the ability of quagga mussels to survive within the hypoxic hypolimnion of some stratified lakes and reservoirs. The oxygen tolerance of both species is likely to vary seasonally and tolerance will be greater if there has been a longer acclimation time towards lower levels.

**Temperature:** Quagga mussels are typically more abundant than zebra mussels at greater depths (Claxton et al, 1998), and so can clearly tolerate constant temperatures of 4°C, as would be found in a permanently stratified hypolimnion. Zebra mussels in Europe can be found at temperatures down to 6°C (McMahon, 1996). The upper thermal limit of quagga mussels appears to be near 25°C while that of zebra mussels is near 30°C (McMahon, 1996).

**Salinity:** Mills et al. (1996) reported a maximum salinity of 4.0 ppt for quagga mussels compared with 7.6 ppt for zebra mussels in the Dneiper-Bug estuary.

**Population-level differences in tolerance**

Just like it may be incorrect to assume that a successful control strategy for zebra mussels can be equally effective against quagga mussels, it is important to consider intraspecific population-level differences in tolerance. First, tolerance of a population to a control agent may be different as a result of inducible defences, where prolonged exposure to small (and sometimes changing) concentrations of a stressor can lead to an up-regulation of defence mechanisms. A good example is the induction of metallothioneins in freshwater organisms which are exposed to low levels of heavy metals. These individuals typically show a much greater ability to tolerate exposure to high levels of heavy metals than individuals that have not been previously exposed to low levels of metals.
The second cause for population-level differences is founder effects. New populations of an invasive species may be founded by a small number of individuals, which therefore may show limited genotypic variability. In the case of dreissenid mussels, founder effects may be more pronounced if populations are founded by a small number of adult mussels rather than an introduction of millions of planktonic veliger larvae. Different genotypes may display phenotypic variability which might therefore include differences in vulnerability to control agents.

Population-level differences in tolerance become clear if we compare data for zebra mussel populations across Europe and North America. Gallardo et al (2013) report dramatically different bioclimatic distributions and tolerances of the species on the two continents. The causes for these differences are likely to be a combination of genetic and inducible defences. Based on these patterns, it would seem prudent that any control strategies that are selected for quagga mussels assume the population we wish to control possesses the greatest tolerance that has been described for the species.
3. Control options

Management of an invasive species may use both reactive and proactive strategies. The focus of this report is very much on reactive strategies, as the purpose is to help identify a rapid response plan following the early detection of an invading population under different possible scenarios of invaded habitat. Proactive responses focus on prevention rather than cure. They might include control of important vectors and pathways that might bring quagga mussels into Britain, and are outside of the focus of this report. However, transport within Britain, once quagga mussels have established, is an important factor to consider in a GB strategy and is discussed at the end of this section.

It can be generally assumed that effective control options used for zebra mussels are worthy of consideration for quagga mussel management. This considerably broadens the literature available as zebra mussels have a longer history of invasion and wider geographical impact than quagga mussels. However, the species-specific and context-specific responses must not be forgotten (see section 2).

Control can be focused upon mussel adults or larvae (veligers). Veligers are much more sensitive to control agents than adults. In practice, a rapid response to quagga mussels in GB is likely to follow discovery of adult mussels and a control scheme targeted at adults is likely to also kill veligers. However, control schemes aimed specifically at veligers are likely to have relevance in management aimed at containing populations through biosecurity measures.

Considering the expense associated with zebra and quagga mussel fouling, it is unsurprising that an immense number of control strategies have been investigated. These control methods can be divided into i) chemical, ii) physical, and iii) biological. Chemical treatment is by far the most widely used technique for controlling zebra and quagga mussels throughout Europe and N. America. However, some emerging data on effective physical control measures for quagga mussels are worthy of consideration. Biological control involves the encouragement or introduction of natural enemies and is unlikely to offer a practical solution.

3.1 Chemical Control

Many chemicals will kill quagga mussels given sufficient concentration and contact time. The acceptability of any particular chemical is determined by considerations of water use (residual concentrations, by-products, impacts on non-target biota), cost and practicality. The primary focus of research has been upon industrial flow-through pipelines which suffer from biofouling nuisances
when encrusted by mussels. Such studies may not be directly transferable to open water scenarios, which is the focus of this report, and so will be touched on only briefly.

Chemicals can be broadly categorised as oxidising and non-oxidising. The suitability of products for responding to a quagga mussel invasion will not only be affected by the function of the water body, but also by whether it is lentic or lotic, its volume its water chemistry and the time of year at which the treatment is undertaken.

### 3.1.1 Oxidising Chemicals

Adult mussels close their shells in response to oxidants. With continuous dosing, mortality may be achieved in a number of ways. First, the oxidant concentration may be so high that the product ingested before closure is fatal. Second, the closed shell does not provide sufficient defence. Third, continuous dosing causes the mussels to remain closed and prolonged closure stresses the mussels by starvation and the need for anaerobic respiration. Fourth, a mussel may open rather than asphyxiate, in which case it becomes exposed to the oxidant.

The primary considerations for the use of oxidants are demand/decay, which governs the dose needed to achieve the necessary residual, and the potential for by-product formation. These factors will be determined by the specific chemistry of the water dosed.

a) Chlorine

Chlorine represents the most effective and popular methods of macrofouling control worldwide. Chlorination remains the favoured control strategy for mussel fouling in many water utilities, but concerns about by-product formation is restricting scope for its application. Similar concerns are likely to restrict its use in open water in GB.

Klerks & Farleigh (1991) showed that chlorine was less effective at killing zebra mussels at lower temperatures (Table 3). Toxicity values are often given as an LT$_{50}$ value, which means the time taken for 50% of the test organisms to die. Matisoff et al. (1996) observed much shorter LT$_{50}$ values for chlorine (Table 4) and this likely reflect the higher water temperatures. Halving the chlorine concentration requires less than double the contact time to achieve the same mortality; to chlorinate to a target mortality it would, therefore, be more economical to apply a lower dose over a prolonged period.
Table 3  Cumulative mortality of adult zebra mussels continuously exposed to chlorine. Raw water pH = 8.3 (Klerks & Fraleigh, 1991)

<table>
<thead>
<tr>
<th>Chlorine dose, mg/l</th>
<th>Free chlorine residual, mg/l</th>
<th>Mortality, 28 days, %</th>
<th>Mortality, 56 days, %</th>
<th>LT50, days</th>
<th>Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.14</td>
<td>10</td>
<td>55</td>
<td>33.7</td>
<td>7-18</td>
</tr>
<tr>
<td>1</td>
<td>0.16</td>
<td>30</td>
<td>94</td>
<td>31.9</td>
<td>7-18</td>
</tr>
<tr>
<td>2.5</td>
<td>1.14</td>
<td>93</td>
<td>100</td>
<td>16.3</td>
<td>7-18</td>
</tr>
<tr>
<td>5</td>
<td>2.76</td>
<td>67</td>
<td></td>
<td>24.4</td>
<td>5-10</td>
</tr>
<tr>
<td>10</td>
<td>7.26</td>
<td>86</td>
<td></td>
<td>19.5</td>
<td>5-10</td>
</tr>
</tbody>
</table>

Table 4.  LT<sub>50</sub> values for chlorine. Raw water pH=8.1. (Matisoff et al., 1996)

<table>
<thead>
<tr>
<th>Chlorine dose, mg/l</th>
<th>LT50, hours</th>
<th>Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>102</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>73</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>46</td>
<td>20</td>
</tr>
</tbody>
</table>

Intermittent dosing of chlorine can help to protect a system from mussel establishment whilst using less overall product. Evans & Sim (1993) dosed a raw water intake with chlorine at a residual of 0.3 to 0.5 mg/l total chlorine for a cycle of 15 minutes on, 45 minutes off, to prevent veliger settling. Compared to a control (no chlorine) they observed reductions of between 90 and 99% in settling. Compared with continuous dosing at 0.5 mg/l total residual chlorine, intermittent dosing reduced chlorine consumption by a factor of between two and three.

Brady et al. (1996) compared mortality of zebra mussels and quagga mussels from exposure to chlorine. Water quality was characterised by a low turbidity (<5 NTU), low organic matter (< 5 mg/l), moderate alkalinity (100 mg/l CaCO<sub>3</sub>) and pH 8. Significantly higher mortality was reported for the quagga mussels. A continuous dose of 1.4 ± SD 0.2 mg/l free chlorine (1.6 ± 0.2 mg/l total chlorine) achieved 100% mortality of quagga mussels in 23 days and 100% mortality of zebra mussels in 37 days.

An extensive literature exists on the optimisation of chlorine dosing to control zebra mussels. However, the wider environmental effects of chlorine suggest that it will be an inappropriate tool for a rapid response to quagga mussels in GB’s open waters. For this reason, only a brief overview has been provided.
b) Chloramines

Chloramine is a chlorine-based oxidant and offers the benefit over chlorine of not forming trihalomethanes (THMs). Chloramines are formed when free available chlorine (HOCl and OCI) reacts with nitrogen-containing compounds. Monochloramine (NH₂Cl) can be used as a disinfectant and has been shown to cause over 90% veliger mortality at concentrations above 1.5 mg/l (van Benschoten et al., 1992). USACE (1994) reports 100% mortality of veligers exposed for 24h to 1.2 mg/l. Chloramine is more stable than chlorine and chlorine dioxide at elevated temperatures, thereby requiring a lower dose to achieve a target residual (Cameron et al., 1989). At two French power plants monochloramine is produced on-site by mixing sodium hypochlorite and ammonium chloride to control mussel fouling (Duvivier, 1993).

c) Chlorine Dioxide

Chlorine dioxide (ClO₂) is used widely in continental Europe by the mixing of sodium chlorite, sodium hypochlorite and hydrochloric acid. Chlorine dioxide is equally effective at all pH levels. Studies by Matisoff et al (1996) suggest that 100% mortality of adult zebra mussels can be achieved with a continuous dose rate of 1 mg/l for 4 days (Table 5). They also concluded that a single exposure of up to 20 mg/l for 30 minutes could achieve a 50% mortality if timed to coincide with warm water temperatures.

Table 5. Cumulative mortality of adult zebra mussels continuously exposed to chlorine dioxide. Raw water pH=8.1 (Matisoff et al., 1996).

<table>
<thead>
<tr>
<th>ClO₂ dose, mg/l</th>
<th>Mortality, 2 days, %</th>
<th>Mortality, 4 days, %, LT₅₀, hours</th>
<th>Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td>0.5</td>
<td>13</td>
<td>57</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>58</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>99</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

Recently, manufacturers have started producing 3000 ppm solutions of chlorine dioxide off-site. An aqueous solution of chlorine dioxide at 3000 ppm is not considered a hazardous substance, but the product will sublime to a gaseous phase at room temperature, which is highly toxic.

While chlorine dioxide does not form THMs (which is the reason why it has often replaced chlorine) it does form other undesirable, regulated by-products such as chlorite and chlorate, albeit at low levels. In addition, studies by the USEPA (Richardson, 1997) found that chlorine dioxide treatment
could lead to elevated bromate and aldehyde by-products such as propanal, benzaldehyde, methyl gloxal and gloxal which may represent regulatory concerns.

d) Ozone

Ozone has been shown to be effective at controlling zebra mussels in contact times similar to chlorine (Matisoff et al., 1996). However, it is a poor solution for open water dosing. First, ozone dissipates in the water rapidly so would only be effective in water adjacent to the dosing point. Second, ozone is relatively insoluble in water compared with chlorine and so requires more extensive delivery mechanisms which are likely to be cost prohibitive. Third, high doses of ozone can result in elevated bromate formation which can present problems for potable supplies.

e) Hydrogen peroxide

Hydrogen peroxide has the reputation for being a benign oxidising agent, dissociating into hydrogen and oxygen and thus leaving no harmful by-products. It is for this reason that it is often used as an algaecide in small open waters.

Relatively high doses of hydrogen peroxide are required to kill veligers and adult zebra mussels. As much as 12 mg/l is required to kill adults and 6 mg/l to kill veligers (Martin et al., 1993; Klerks et al., 1993). Matisoff et al. (1996) observed no mortality of zebra mussels after 30 minutes contact time and a concentration of 30 mg/l. The high doses and relatively high costs of hydrogen peroxide have precluded it from being used as a mussel control agent.

f) Potassium permanganate

Potassium permanganate offers a credible option for a rapid response to quagga mussels. It is widely used in North American municipal facilities for water purification and can help to protect against oxidation of iron and manganese. It can also protect against THM formation. Giacomo & Wymer (1997) established effective control for adult zebra mussels at a concentration of 2.0 mg/l and veliger settlement was prevented at a concentration of 1.0 mg/l. Similar mortalities were reported by Klerks & Fraleigh (1991; Table 6).

Potassium permanganate is normally provided as a granular solid, so is easy to handle and dose. For water sanitation it is typically mixed as a solution of around 10 g/l. The negative aspects of this product as a rapid response tool are the effects on non-target biota, the relatively high cost and the discoloration (pink) of the treated water.

<table>
<thead>
<tr>
<th>MnO4 dose, mg/l</th>
<th>MnO4 residual, mg/l</th>
<th>Mortality, 28 days, %</th>
<th>Mortality, 56 days, %</th>
<th>LT50, days</th>
<th>Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.24</td>
<td>0</td>
<td>0</td>
<td>&gt;56</td>
<td>11</td>
</tr>
<tr>
<td>1</td>
<td>0.53</td>
<td>24</td>
<td>52</td>
<td>49.8</td>
<td>11</td>
</tr>
<tr>
<td>2.5</td>
<td>1.25</td>
<td>96</td>
<td>100</td>
<td>10.7</td>
<td>11</td>
</tr>
</tbody>
</table>

g) Iron oxide

Iron oxide (ferrate; FeO₄²⁻) is considered a powerful and environmentally friendly oxidant. Treatment by Fe(VI) is thought not to produce any mutagenic/carcinogenic by-products and the final product is a reduced, non-toxic Fe³⁺ ion.

One company, Ferrate Treatment Technologies (http://www.ferratetreatment.com/ballastwater.htm), has developed an on-site ferrate-generating unit (Fig. 2) that claims to be effective against invasive pests. Tests have focussed in ballast water systems, where the company reports success with doses of 1-4 ppm. Ballast water treatment focuses on planktonic larvae, and so the treatment may not be effective against adult quagga mussels.

Figure 2 Ferrator unit for on-site production of iron oxide (http://www.ferratetreatment.com)
3.1.2. Non-oxidising chemicals

The majority of non-oxidising chemicals used in the treatment of zebra and quagga mussels are designed for the use of one-off, end-of-season treatments rather than continuous dosing. This suitability to a short dose targeted at adult mussels makes them potentially more well suited than oxidising chemicals for a rapid response in open water systems.

a) Proprietary molluscicides

A range of non-oxidising commercial molluscicides are available on the market, although these products are typically toxic to a wide variety of organisms and certainly not mollusc-specific. Typically, molluscicidal products achieve success by not inducing the valve-closing response seen in mussels when exposed to many toxicants. They are usually targeted at recently-settled juvenile mussels or veliger larvae, so may not offer an effective protection against an adult population of mussels. Formulations typically focus on quaternary amines (e.g. Clamtrol products from GE Betz) or on isothiazolones (e.g. Bulab 6002 from Buckman USA). Due to the toxic nature of the products, they are usually neutralised after treatment through the addition of a slurry of bentonite clay, which in itself may present some operational and environmental challenges. Relatively little published information is available on the effectiveness of Clamtrol and Bulab as a molluscicide and the products are not available as a commodity. Instead, a service is given by a company representative. Calgon H-130M is a non-oxidizing liquid organic compound containing a solution of polyquaternary alkyl ammonium registered for use as a molluscicide in industrial once-through freshwater cooling water systems. Calgon H-130M controls zebra mussel and the Asiatic clam in veliger, juvenile, and adult forms. Because of its need for proper deactivation prior to discharge, it is sold only as part of a complete Calgon mollusc treatment application service, and is to be used only with supervision from a Calgon representative. Typical doses are 1 to 10 mg/l for 24h, four times per year. To our knowledge, Calgon, Calmtrol and Bulab products are not marketed in the UK.

Bayluscide is registered as a lampricide (for control of invasive sea lampreys) and a molluscicide. The active ingredient is Niclosamide (2', 5-dichloro-4'-nitrosalicylanilide), and the product is typically used in combination with other products as a control agent. It can achieve 100% mortality in molluscs at a dose of 1.0-5.0 mg/l (Schnorbach et al., 2006). However, the product is also highly toxic to fish, with reported LC50 levels of 0.05 mg/l for rainbow trout and 0.23 mg/l for goldfish. The half life of Bayluscide ranges from 0.8 to 2.5 days depending on water quality (Calumpang et al., 1995).

Mexel is a filming agent based on fatty amines, and is derived as a byproduct of the petrochemical industry. The active ingredient is an alkyl trimethylenediamine. Mexel has an unusual mode of
activity in that it inhibits the byssal thread (‘beard’) production in mussels, although it is not a species-specific toxin. Giamberini et al. (1994) found byssus production could be inhibited with doses of 2 mg/l. The manufacturers recommend a daily dose for 30 minutes at 4-5 mg/l to keep systems free from zebra and quagga mussels. Unlike many other molluscicides, Mexel does not require neutralising. High levels of suspended solids in the water column require higher doses of Mexel to achieve success.

b) Bacterial toxins – Zequanox

A toxin derived from a common soil bacterium, *Pseudomonas fluorescens* (Strain CL145A), has been identified as a control agent specific to zebra and quagga mussels. Toxicity is retained when the bacterium is dead. The product is being commercialised as Zequanox by Marrone Organic Innovation Inc., and trials have been conducted by Ontario Hydro, Canada. The active ingredient is a secondary metabolite which is degradable within 24 hours (Molloy et al., 2013). Molly et al. (2013) reported mortality of 72 to 96% of adult zebra mussels when exposed to 100 mg/l Zequanox for 24 hours.

Trials in open water have been conducted within enclosures at a number of open water bodies in the USA, and also in Ireland (by Frances Lucy at the Sligo Institute of Technology). No experimental data are available in the public domain, so the efficacy of the product is hard to assess at this time. However, until the product is commercially available it is difficult to consider this option further. The high dose rates required for success, combined with a likely high cost, will preclude its use in large water bodies. The manufacturers claim low toxicity to non-target organisms, although lab trials have shown some toxicity to crustaceans (Dan Molly, personal communication). There have been questions raised about the likelihood of specificity to zebra and quagga mussels from a bacterium isolated from soil in a location well outside the mussels’ native range.

c) Encapsulated control agents – BioBulletts

Most bivalves are able to sense chlorine and other oxidants in the water and respond by closing their valves for periods of up to three or four weeks. Aldridge et al. (2006) have developed a method to encapsulate the active ingredient for mussel control in an ‘edible’ coating. The individual particles are of the size commonly fed upon by zebra and quagga mussels (20 µm; Fig 3). The mussels filter the particles from the water without realising they have swallowed a ‘poison pill’. Uneaten particles are engineered to degrade within hours of entering the water system.
The product is marketed by BioBullets Limited (www.biobullets.com) under the commercial names Silver Bullets 1000 and Silver Bullets 2000 (SB1000 and SB2000). SB1000 and SB2000 offer the advantage of being approved for use in UK raw waters by the Drinking Water Inspectorate (DWI 56/4/852 Silver Bullets 1000. DWI 56/4/1000 Silver Bullets 2000). The UK Environment Agency has given discharge consents for the release of water treated with SB1000 into recipient rivers and streams as part of trial permits for some UK water treatment works.

Successful trials of SB1000 have been conducted by South Staffs Water, Severn Trent Water and Anglian Water. Recommended doses are 10mg/l for SB1000 and 2.5 mg/l for SB2000 with continuous treatment for 10 days. Anglian Water have reported a 63% increase in pipeline throughput following treatment with SB1000.

To date, SB1000 has been used to achieve only partial kills of mussel populations, as this protects the waterworks from mass inundation of mussel biomass. However, independent trials in The Netherlands by KEMA have achieved 100% kills of both zebra and quagga mussels at higher doses of product (www.biobullets.com). The largest volume of water to have been treated to date using SB1000 is 1500 megalitres per day for 10 days (1.5 million cubic metres per day).
BioBullets have been specifically designed to treat flow-through systems. Open water systems are less well suited to the standard formulations, but the company is developing delivery methods that can focus product towards the bed of lakes and rivers, which is where the quagga mussels will reside.

d) Endod

There has been considerable research undertaken on Endod, a natural molluscicide found in the Ethiopian soapberry. The berry is used for clothes washing in Africa. Lemma (1965) found that there were many dead snails downstream of washing stations. Endod has been shown to kill mussels at concentrations of 10 mg/l, whilst being apparently non-toxic to mammals (Lambert et al., 1991). Lemma & Yan (1974) reported that the toxic effects of the product disappeared after 1 to 2 days, indicating the product was readily biodegradable.

Wright & Magee (1997) tested Endod extracts against quagga mussel larvae and reported that the product was less effective than many other control agents. Endod is not commercially available and so its value as a response tool for quagga mussels is limited.

e) Coagulants and polyelectrolytes

Poly-diallyl-dimethyl-ammonium chloride (polyDADMAC) compounds are DWI approved for use as coagulants in water treatment. They also form the active component of products used as molluscicides in North America (e.g. VeliGON, Calgan Corporation). The products can remove veligers through their flocculating effects. Adult mussels are also vulnerable to polyDADMACs. Costa et al. (2008) reported 48h \( LC_{50} \) values for polyDADMAC to adult zebra mussels of 10 mg/l during summer months, although this increased considerably during the winter. Muia et al (1993) reported considerably higher mortalities, with 100% kill at 22°C, 2 mg/l and a 24h dose. The polymer is toxic to fish and aquatic invertebrates, but degrades relatively quickly within the open water.

In 2009, a replicated, controlled laboratory study was conducted on quagga mussel larvae from Lake Mead, Nevada (Britton and Dingman 2011). It found that exposure to the quaternary ammonium, alkylidimethylbenzylammonium chloride, (ADBAC) effectively killed them. A 3% solution of Sparquat 256® (corresponding to 1500 ppm benzalkonium chloride) achieved 100% veliger mortality after one hour.

Other inorganic coagulants, such as alum, have the potential for control, but doses in excess of 20 mg/l are required making them unlikely candidates for a rapid response to quagga mussels.
f) Potassium salts

Potassium compounds are toxic to most bivalves, causing changes to gill physiology and driving osmotic shock. Lewis (1996) used potassium chloride in flow-through chambers to show that 100% mortality in adult zebra mussels could be achieved in 52 days. A shock dose (600 mg/l KCl) killed small mussels (7-11 mm) in just 48 hours at a power plant in the Moselle River (Khalanski, 1993). Potassium can also cause mussels to keep their valves open for protracted periods (Wildredge et al, 1996) which can increase their vulnerability to other control agents (Lewis, 1996).

Case Study: Millbrook Quarry, Virginia

Zebra mussels were discovered in Millbrook Quarry in 2002, representing the first record for the State of Virginia. The quarry has a maximum depth of 28m, surface area of 0.05 km$^2$ and is a popular recreational diving site (the likely source of the mussels). The threat of zebra mussels to nearby industry and ecosystems resulted in the development of an eradication plan using potassium chloride.

To kill the zebra mussels, the entire quarry was injected with 660 m$^3$ of potassium chloride solution over a 3-week period from January 31 to February 17, 2006. The solution was delivered each morning to the site, and then pumped from land-based storage tanks through a floating supply line to a 7 metre work boat outfitted with a specially designed diffuser assembly on its bow. Potassium concentrations throughout the quarry and in adjacent surface waters were measured each weekend during the treatment. The target concentration was 100 mg/l. Sampling at various depths and locations in the quarry after treatment revealed potassium concentrations ranging from 98 to 115 ppm, and no potassium leakage from the quarry into adjacent waters was detected.

Figure 3. Injection of potassium chloride solution into Millbrook quarry.
Concentrations of potassium were monitored at various depths along transects established throughout the quarry, both during and after "charging" of the quarry, to ensure that lethal concentrations were achieved and maintained. Then, several weeks after treatment was completed, four separate methods of confirming eradication of the infestation were implemented. First, over a thousand mussels were scraped from rocks at numerous sites around the quarry during informal assessments, revealing no live mussels. Second, SCUBA divers who had documented the extent of the infestation during pre-eradication studies conducted a visual inspection of the quarry, searching for live zebra mussels but finding none. Third, a video survey further confirmed the dead zebra mussels through use of a robotic camera. Finally, eighty bioassays of 100 live zebra mussels each were placed at various locations and depths throughout the quarry and thus exposed to the treated quarry water. After 31 days of exposure to the treated quarry water, 100% of the test mussels had died. None of the 100 "control" zebra mussels held in untreated water died during their bioassay period. Other aquatic wildlife including turtles, fishes, aquatic insects, and snails were reportedly unharmed by the treatment.

The managers of the trial suggest that at the concentrations of KCl used in the quarry (100 mg/l) potassium poses no human health risks, nor will it harm any non-molluscan aquatic wildlife, vegetation, or terrestrial wildlife inhabiting the project site. They further suggest that by US standards, it would be necessary to drink 72 litres of Millbrook Quarry water to consume an adult’s daily recommended dose of potassium.

Potassium treatment in Millbrook Quarry provides the added benefit of long-term protection of Millbrook Quarry against future infestation by zebra mussels. Estimates are 33 years. The project cost £260,000 at 2006 prices. However, the cost of potassium has increased considerably since then.

g) Copper Ions

Copper is toxic to most aquatic species because it binds to gill membranes, which causes tissue damage and interferes with osmoregulation and gas exchange (USEPA 2008). Copper sulphate has been used as a treatment for Island Apple Snails, an invasive mollusc in Florida (Haller 2007) and has been used to effectively reduce snail populations in catfish ponds (Mischke et al.2009). Copper sulphate is also toxic to all life stages of zebra mussels (Kennedy et al. 2006). Various copper products have been regularly used in industrial settings as an effective antifouling coating due to its toxicity to zebra mussels. Dormon et al. (1996) reported that zebra mussel fouling was reduced dramatically, but not entirely prevented, when using copper screens.
The toxicity of copper in open water is influenced greatly by the hardness of water, and so extrapolation from the literature must be undertaken with caution. Blume et al. (1994) found that dreissenid veligers were prevented from settling at a continuous dose of 10 ppb copper ion. A dose of 14-81µgCu/l for 24h was found to result in almost 100% mortality of zebra mussel veligers (Kennedy et al, 2006).

Copper ion generators are commercially available (e.g. MacroTech Copper Ion generator, www.macrotechinc.com) and have been used in some US power plants to manage biofouling problems. Copper has historically been dosed into freshwaters as an algicide in the form of copper sulphate (e.g. Cutrine-Ultra, www.alliedbiological.com).

Watters (2008) conducted extensive laboratory tests on a product called EarthTec (Earth Science Laboratories, USA; earhsciencelabs.com), a formulation of copper sulphate pentahydrate and an acid called ‘ET-3000’. The product is registered by the USEPA as an algicide/bactericide and has approval in the USA as a drinking water additive. Trials were conducted against all life stages of quagga mussels. For adult mussels, 100% mortality was reached after 96h using doses at 17 mg/l and higher. At lower concentrations (10 mg/l and lower) laboratory tests never yielded 100% mortality in adults, although trials ran only for 7 days.

**Case Study: Offlutt Lake, Nebraska, USA**

In September 2008 a zebra mussel eradication scheme was attempted using copper sulphate pentahydrate within Offlut Base Lake, Nebraska (Morris et al, 2009). The use of potassium chloride was considered as an alternative, but was determined to be cost-prohibitive and logistically unfeasible, with the need for 340 tonnes of product for treatment at Offlutt Lake.

The lake surface area is approximately 0.5 km$^2$, mean depth of 3m and maximum depth of 5m and so an approximate volume of 1.5 million m$^3$. To treat the water, 12.25 tonnes of product was applied via vortex spreaders mounted on a pontoon boat. Hand application was completed in drainage ways and other areas that could not be reached with the boat due to obstructions (docks, trees, rocks, etc.). The full quantity of chemical was applied within a 30 hour timeframe. A global positioning system (GPS) unit loaded with ArcView geographic information system (GIS) software was used to assist in navigation of the lake to ensure full coverage was achieved. During April 2009 a second dose of copper sulphate at the same concentration was added to the lake.
**Figure 4.** Boat-based vortex-spreader used for dosing copper sulphate pentahydrate into Offlutt Base Lake

**Figure 5.** GIS trace showing the uniform coverage of the dosing boat at Offlut Base Lake.
During the 2008 dose copper concentration in the lake was informally monitored from the shore during the copper sulphate application. The maximum measured concentration during application was 1.5 ppm, with an average concentration of approximately 0.7 ppm. A full lake-wide delineation was completed approximately 24 hours following the completion of the treatment. Copper analysis was performed at seven locations throughout the lake, at the top, middle and bottom depths. Copper concentrations varied from 0.00 to 0.73 ppm, with a mean concentration of 0.25 ppm. The copper concentrations varied widely and copper was not uniformly mixed throughout the lake. However, since no measured concentrations exceeded 1.3 ppm, no usage restrictions were required as part of the regional compliance criteria (Special Local Needs Label).

A second copper characterization was performed in October 2008, a month later at the same seven locations as the 24-hour characterization. Results of this characterization indicated that copper concentrations of the lake have become fairly uniform and much of the copper had precipitated out. Concentrations ranged from 0.04 to 0.20 ppm, with a mean concentration of 0.10 ppm.

Post treatment monitoring indicated that all zebra mussels had been killed. The non-specific nature of copper is revealed by the mortality of 19 tonnes of fish during the trial. All fish were buried in pits adjacent to the lake.

Figure 6. Dead fish at Offlut Base Lake illustrating the impact on non-target biota of dosing copper sulphate.
h) pH reduction

The precise response of zebra and quagga mussel veligers and adults to pH is affected greatly by acclimation. As a general rule, in North America a pH of <7.0 will not support quagga mussels while high levels of fouling can be expected at pH 8.2-8.8 (Table 2). Acidity affects the ability of bivalve molluscs to secrete their calcareous shells.

A study in calcium-rich (41 mg/l) waters in Lake Ontario, Canada, used phosphoric acid to adjust the pH to 6.9, 7.1 and 7.3 (Claudi et al., 2012). Both zebra and quagga mussels showed approximately 40% mortality at pH 6.9 after 10 weeks of exposure. Settlement of new mussels was almost entirely stopped at pH 7.1 and 6.9. These results relate to calcium-rich waters and the authors suggest that more dramatic effects might be observed in water with lower background calcium levels. The data suggest that correction to pH 6.9 may not be sufficiently low to achieve a successful eradication, although mortality was followed for only 10 weeks.

Some, but very few, UK water treatment process require downward pH correction (e.g. the Sirofloc process, which requires a pH of 4 to 6). This may mean that pH correction of intake waters could be feasible (e.g. to 6.9) if quagga mussels were observed in storage reservoirs, although in many sites pH may need to be corrected upwards for other treatment processes to be effective. In many systems, an acidic pH may affect the integrity of pipelines and cause corrosion of riparian structures.

i) Oxygen reduction

A controlled laboratory study conducted on zebra mussels from the Niagara River, New York (Matthews and McMahon 1999) found that they could survive extreme levels of hypoxia. Mussels survived under oxygen stress (<5% saturation) for an average of 3-4 and 38-42 days at 25°C and 5°C, respectively. Mussels that were acclimated to lower temperatures survived hypoxia for longer and larger mussels were more tolerant than smaller ones. The study also found that mussels did not attach to walls under hypoxic conditions.

One of the most effective ways of reducing oxygen levels in a static water body is through the addition of oxygen-scavenging chemicals such as sodium metabisulphate. A target of <3 mg/l dissolved oxygen is thought to be sufficient to prevent mussel persistence (Mackie & Claudi, 2010). Sodium metabisulphate may be appropriate for quagga mussel eradication in small, enclosed water bodies but the large volumes of product required would prevent it from representing a viable option in flowing waters or large waterbodies. In addition, hypoxia can encourage growth of sulphate-reducing bacteria, which may cause corrosion of infrastructure.
An emerging approach to oxygen deprivation is the use of plastic sheeting to smother the benthos. This has been used effectively in the control of Asian clams (*Corbicula fluminea*). In Lake Tahoe, USA, a team of divers supported by two boats and a barge deployed large rolls of aspen shavings covered by non-gas-permeable plastic sheeting on the lake bottom to control Asian clams in specific areas (Figs. 7, 8). The aspen shavings absorb oxygen, thereby decreasing the amount of time the sheeting needs to stay in place. Nearly 2,000 m$^2$ of the lake bottom was covered and left for 120 days between July and November 2010. Upon removal there was an estimated 98% reduction in Asian clam population and this remained low (90%) one year later (Wittmann et al., 2012).

![Deployment of aspen sheeting beneath a plastic sheet on the bed of Lake Tahoe to control Asian clams](http://ca-sgep.ucs.edu)

**Figure 7.** Deployment of aspen sheeting beneath a plastic sheet on the bed of Lake Tahoe to control Asian clams (from http://ca-sgep.ucs.edu)

![Placing of plastic sheeting over a frame so that rocks surfaces could be smothered](http://ca-sgep.ucs.edu)

**Figure 8.** Placing of plastic sheeting over a frame so that rocks surfaces could be smothered (from http://ca-sgep.ucs.edu)
The use of plastic sheeting provides the opportunity for adding biocides beneath the sheeting to accelerate the die-off and to reduce the quantity of biocide required. However, if the mussels close their valves in response to the stressful conditions they may be less exposed to the biocide.

j) Salinity increase

Wright et al. (1996) found that survival of zebra and quagga mussels, under increasing salinities and temperatures, depended on larvae stage at the point of exposure. Overall, zebra mussels could tolerate higher salinities than quagga mussels. 6% of 3-5 day old zebra mussel veliger larvae survived exposure in 4ppt, whereas 22% of larvae exposed at day 11 survived. Quagga mussel larvae did not settle and by day 30 in 8ppt 0.1% remained alive.

Ellis and MacIsaac (2009) found that zebra and quagga mussel larvae from a lake in Canada died after one hour in water with 30ppt salinity. When salinity levels were changed gradually, larvae were all dead after four hours. Adult zebra and quagga mussels were more resistant to salinity than were the veligers. More than two thirds of the mussels survived 5 hours in water with 30ppt salinity. It did not make a difference if the water increased in salinity levels gradually, and some adult mussels survived for two days.

3.1.3 Non-chemical control

a) Thermal shock

Thermal treatment of boats and equipment is widely considered to be a more acceptable approach than the use of chemical treatment agents and high pressure sprays due to their adverse effect on hull surfaces, damaging impact on equipment, storage and disposal requirements, and their toxicity to recipient waterways (Beyer et al., 2011). A number of studies have described the thermal tolerance of quagga mussels, but from a management perspective it is the effect of a thermal shock that is important. This means that the tolerance of quagga mussels to heat treatment is likely to vary through the year. It has been reported that quagga mussels are less tolerant of heat than zebra mussels (Spidle et al., 1995) so it is reasonable to assume that any treatment regimes that have been shown to be effective against zebra mussels will also be effective against quagga mussels.

Table 6 summarises the key findings for the heat treatment of adult quagga mussels. A higher temperature requires a shorter exposure time. Bruijs et al. (2010) found that immersion at 33 °C for
two hours could result in 100% mortality. From a practical perspective, equipment and boats will require a higher temperature for a shorter time. Morse (2009) recommends 60 °C for 10 seconds in the management of zebra mussels, and this should also be effective for quagga mussels. Discussions in the UK for the heat treatment of boats fouled with killer shrimps (*Dikerogammarus villosus*) concluded that hot water jets cooled very quickly as they left the lance, and so may not be entirely effective. There were also concerns over the safety of boat users exposed to hot water sprays. As a consequence, pressure washing was selected in preference. The attachment of quagga mussels to solid surfaces with their byssus threads may reduce the effectiveness of pressure sprays as a removal approach.

Table 6. Minimum temperatures and durations required to induce 100% mortality in adult quagga mussels.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Duration (s)</th>
<th>Application technique</th>
<th>Pre-treatment</th>
<th>Reference</th>
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<tr>
<td>80</td>
<td>5</td>
<td>hot water spray (14.07 kPa)</td>
<td>2 weeks immersed in lake water at 11.9 °C ± 1.6 °C</td>
<td>Comeau et al. (2010)</td>
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<tr>
<td>70</td>
<td>5</td>
<td>hot water spray (14.07 kPa)</td>
<td>2 weeks immersed in lake water at 11.9 °C ± 1.6 °C</td>
<td>Comeau et al. (2010)</td>
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<tr>
<td>60</td>
<td>5</td>
<td>hot water spray (14.07 kPa)</td>
<td>2 weeks immersed in lake water at 11.9 °C ± 1.6 °C</td>
<td>Comeau et al. (2010)</td>
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<tr>
<td>54</td>
<td>10</td>
<td>hot water spray (14.07 kPa)</td>
<td>2 weeks immersed in lake water at 11.9 °C ± 1.6 °C</td>
<td>Comeau et al. (2010)</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>hot water spray (14.07 kPa)</td>
<td>2 weeks immersed in lake water at 11.9 °C ± 1.6 °C</td>
<td>Comeau et al. (2010)</td>
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<td>43</td>
<td>300</td>
<td>Immersion</td>
<td>Immersed for 24 hours at 20 °C</td>
<td>Beyer et al. (2011)</td>
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<tr>
<td>40</td>
<td>40</td>
<td>hot water spray (14.07 kPa)</td>
<td>2 weeks immersed in lake water at 11.9 °C ± 1.6 °C</td>
<td>Comeau et al. (2010)</td>
</tr>
<tr>
<td>38</td>
<td>1200</td>
<td>Immersion</td>
<td>Immersed for 24 hours at 20 °C</td>
<td>Beyer et al. (2011)</td>
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<tr>
<td>33</td>
<td>7200</td>
<td>Thermoshocks</td>
<td></td>
<td>Bruijs et al. (2010); Rajagopal et al. (2010)</td>
</tr>
</tbody>
</table>

b) Desiccation

Draw-down offers a viable and effective option for a rapid eradication of quagga mussels in some waterbodies. In Spain, the agricultural sector routinely employs lowering of water levels or emptying irrigation systems in winter, followed by removing dead mussels with brushes (Duran et al., 2010). The vulnerability of quagga mussels to desiccation will be dependent on the time of year, the size of the mussels, ambient temperature and ambient humidity.
Ricciardi et al. (1995) found in the laboratory that all quagga mussels died within a 3-5 days of emersion at 20°C at 10% humidity. In comparison, mussels died within 5-7 days at 50-95% humidity. At lower temperatures more mussels survived; at 10°C and 95% humidity, they survived more than 10 days. Larger mussels were more resistant to emersion than smaller ones. Low humidity and high temperature conditions for long exposure periods led to more weight-loss through desiccation.

All quagga and zebra mussels taken from a Lake Erie power station died after 100 hours emersion at 33% humidity and 15°C (Ussery and McMahon 1995). In comparison, it took 100-300 hours at 53-75% humidity, and more than 300 hours at >95% humidity levels to achieve a 100% kill. Quagga mussels were more vulnerable to desiccation than were zebra mussels.

c) Hand removal

From 1999-2007, a trial was conducted in Lake George, USA, with the aim of removing zebra mussels manually (Wimbush et al. 2009). It found that intense manual removal efforts by SCUBA divers successfully eradicated a colonising population of less than 30 000 zebra mussels, affecting an area of about 3900 m². About half of the population were removed in the first two months. By seven months 90% had been removed. Data suggested that mussels had not reproduced since the project began. Six further populations were subsequently found at other locations in the lake, and similar removal efforts seemed to be similarly successful. Immediately after discovering adult mussels, the affected area was divided into nine sections. Divers removed mussels by hand. In the first year, they focused on a small area with the highest mussel concentration. They recorded how many mussels were removed. They measured shell lengths of 16-100% of mussels removed per year. At water temperatures above 12°C (spawning threshold), samples were checked for larvae at least every 2 weeks. Larval settlement and recruitment was monitored using settlement plates. The authors suggest that if highly intensive and regular removal it is feasible that the population can be driven to a level which becomes unsustainable.

The Wimbush et al. (2009) study is the only example where successful control by hand removal has been reported. While the process offers the appeal of having minimal impact on non-target biota and water quality, it is highly unlikely to result in an eradication as not all mussels will be found. It does, however, have the potential to limit population growth if removal effort is sufficiently intensive. Indeed, Duran et al. (2010) reported that mechanical removal of zebra mussels from large dams in the Ebro basin, Spain, was too slow (15 minutes per 1 m²), labour-intensive and expensive resulting in the method being impractical.
d) Biological control

Crayfish, diving ducks and some fish feed on zebra mussels and all have the potential to control quagga mussel infestations. Unfortunately, when zebra and quagga mussels reach high densities their byssus threads entwine and they become considerably more difficult to prize apart. As a result, mussels can only be controlled by biological means when population density is relatively low and under such circumstances quagga mussels are unlikely to be a major problem. Furthermore, under low densities they may go undetected. No specific natural enemies have yet been identified.

Declines in quagga mussels in parts of Russia have been attributed to fish predation (Zhulicov et al., 2006). In the southwestern United States, Wong et al. (2013) found that stocking of redear sunfish (*Lepomis microlophus*) at a density of 0.42 fish/m$^3$ in an infested lake enclosure appeared to suppress growth and recruitment, although they do not report eradication. It is likely that Ponto-Caspian fishes may be especially well adapted to a diet on dreissenid mussels, and Andraso et al. (2011) report that round gobies (*Neogobius melanostomus*) larger than 60mm body length are effective predators of quagga mussels. Round gobies would constitute an invasive species in their own right in GB (Gallardo & Aldridge, 2013).

Eggleton et al. (2004) suggest that the slow spread of zebra mussels in some parts of the southern United States may be the result of predation by native molluscivorous fishes. Native molluscivorous fishes in Great Britain include roach (*Rutilus rutilus*), although their potential as a control agent for dreissenid mussels has not be studied.

e) Filtration

Mechanical filtration is capable of removing all quagga mussel veligers from water transfer systems. Microfiltration has been employed in the Ebro system, Spain, to protect systems receiving Ebro water from becoming fouled by zebra mussels (Concha Duran, CHE Spain, pers. comm.). Quagga mussel veligers are 40µm in diameter, but can pass through smaller size meshes by distorting. For example, a 40 µm absolute mesh was installed at Nanticoke Power Plant, Canada, and achieved between 96 and 100% filtration of veligers. It is therefore generally recommended that mesh size should be 20µm (Mackie & Claudi, 2010). Caution should be taken when interpreting the size of a mesh. ‘Nominal value’ is an arbitrary value typically corresponding to 98% removal of particles, and as such may not offer full protection.

Filtration does not offer a potential eradication option, but may be worthy of more detailed consideration if transfer of quagga mussels into new water bodies is a concern.
f) UV light

Ultraviolet radiation is highly effective at controlling bivalves for as long as they have a transparent shell. This means that veligers are vulnerable, but juveniles and adult mussels are not. Mercury lamps can be an effective method for delivery UV light, and can prevent settlement of veliger larvae in waters of low turbidity. However, juvenile and adult mussels that translocate between sites are not affected by the UV.

Wright et al. (1996) found that using light wavelengths of 254, 280 and 297 nm at doses of 12.5, 11.7 and 25.7 mW cm$^2$s, respectively, produced mortality rates of 100%, 94% and 84%, respectively, in quagga mussels. Wright et al. (2007) also found that 60 seconds of exposure to 254 nm caused 100% mortality of quagga mussel veligers within eight days.

UV light does not offer a potential eradication option, but may be worthy of more detailed consideration if settlement of quagga mussels at particular locations is undesirable or if transfer into new water bodies is a concern.

g) Freezing

Clarke & McMahon (1993) investigated the effect of freezing on zebra mussels held singly or in clusters out of water. They found that clustered mussels took approximately twice the time to die as single mussels (Fig. 9). Their results suggest that dewatering a site during sub zero temperatures (-1.5 °C for 15 hours) may be especially effective at killing zebra and quagga mussels.
Figure 9. Freeze survival of separated and clustered adult zebra mussels taken out of water. LT$_{100}$ values indicate the times to achieve 100% mortality (from Clarke & McMahon, 1993).

h) Other options

There are a wide range of additional control strategies that have been tested for zebra and quagga mussel control. They are not reviewed here in detail because they are not considered appropriate for a rapid eradication or containment response. Most have been developed for control of mussel fouling within an industrial setting.

**Electric currents** can induce valve closing in veligers and stop them settling at sensitive sites (Smythe & Dardeau, 1999).

**Acoustic waves**, such as those produced by Plasma Sparkers, can prevent settlement on pipe surfaces and can induce shell closure, but risks damage to the infrastructure (Schaefer & Claudi, 2004).

**Antifouling coatings** slowly release toxicants (typically copper-based) into the water (Kilgour & Mackie, 1993). Anti-foulant coatings made from silica can reduce settlement by reducing the
attachment success of the byssus thread. However, anti-foulant coatings typically last no longer than 6 years and have been estimated to cost approximately £80 m$^2$ over a five-year period (Wells & Systema, 2009).

Magnetic fields have been suggested to affect elemental uptake and cause direct damage to mussel gills (Barnes et al., 1998). However, the methodology has never been used at a large scale and quantitative data on efficacy is rather limited.

### 3.4. Combination treatments

Perhaps one of the greatest recent advances in the control of dreissenid mussels has been the recognition of the synergistic effects of using some agents in combination. The basic concept is that if one agent is used at a low dose to physiologically stress the mussels, then a second agent can achieve mortality at a dramatically reduced concentration.

At the most well known level, the toxicity of control agents is often temperature-dependent. Costa et al. (2009) showed that the toxicity of control agents to zebra mussels could vary 20-fold depending on the time of year. Typically, mussels were most easily killed in June when the mussels were of a lower body condition due to recent spawning, and the mussels had an elevated filtration rate which exposed them to higher doses of product (Fig. 10).

![Figure 10](image)

**Figure 10.** Seasonal patterns in susceptibility of zebra mussels in the UK to potassium chloride (Costa et al., 2009). Similar patterns were found for other control agents. The lower LC$_{50}$ values for the summer months indicate a greater vulnerability of the mussels.
Carbon dioxide has also been shown to be an effective control agent in combination with other products. CO$_2$ can have a narcotising effect on mussels, which can help to bypass the valve-closing response that they often show when exposed to control toxicants. Payne et al. (1998) and Polman (KEMA, pers. comm.) have shown that pre-treatment of zebra mussels with carbon dioxide increases their sensitivity to chlorine treatments.

The toxicity of the mixed biocides potassium chloride and polyDADMAC to both adults and veligers was evaluated in laboratory static bioassays by Costa et al. (2011). The combined toxicity of the chemicals was observed to depend on the life stage of the mussels. For adults, it was shown to vary with the magnitude of the response under consideration. When producing low lethal effects (below around 25% mortality), the chemicals acted synergistically on the mature organisms and tended to be additive. At high mortality levels, they operated more than additively. In contrast, regardless of the response level under consideration, the toxins appeared to exert additive or less than additive effects on the veligers depending on the potassium chloride dosage.

Figure 11. The combined effects of two control agents (polyDADMAC and KCl) on adult zebra mussels held in static laboratory aquaria (Costa et al., 2011)
3.5 Options for containment and biosecurity

If quagga mussels are identified in a British freshwater it will be important to minimise the risk of dispersal to other water bodies. Containment will be very difficult in river systems because veliger larvae, translocating juveniles and adults could move out of the system very quickly. However, in static and isolated waterbodies containment may well be an important primary consideration.

Overland dispersal may occur through transport of veligers within bait buckets and boat engines, or from adults and juveniles attached to recreational equipment. Veliger larvae can remain in the water column for three to four weeks, and so can withstand considerable journeys (Claudi & Mackie, 1993). Adult quagga mussels can tolerate overland dispersal of three to five days transport from infested waterbodies (Ricciardi et al, 1995) and can attach to the stems of water plants which might be carried on boat trailers and engines. Adult zebra and quagga mussels can survive a maximum of 22 days in water-saturated air (>95% relative humidity) at 15°C (Ussery & McMahon, 1995).

The possession of a byssus means that structures that have been in the water body for a prolonged period may be particularly important vectors is they are moved to another waterway. This means that boat hulls, removed macrophytes (especially reeds) many need special attention. It is also likely that after initial discovery there will be an intensive period of surveys for the mussel. Strict biosecurity measures should be taken, with a standard procedure to sampled progressively downstream within any single waterbody.

Experience in North America suggests that the most important pathway for spread of quagga mussels out from an isolated waterbody is through movement of contaminated fishing gear and boats, rather than through water currents, flooding, attachment to animals or transport in fish guts (Padilla et al., 1996; Buchan & Padilla, 1999; Johnson et al., 2001; Britton & McMahon, 2005). In The Netherlands, quagga mussels have spread through interconnected waterbodies of the Meuse system, but have not colonised more isolated water bodies. Matthews et al. (2012) attribute this spread primarily to quagga mussel fouling of boat hulls.

At present, the standard biosecurity in Britain’s freshwaters in the Check, Clean, Dry initiative. The initiative is likely to provide an important control measure for overland dispersal of quagga mussels, although some additional precautions may be appropriate, especially during the early stages of discovery (Table 7).
Table 7. Suitability of the Check, Clean, Dry procedures for the containment of quagga mussels in an isolated GB freshwater.

<table>
<thead>
<tr>
<th>Current CCD recommendations</th>
<th>Suitability for quagga mussel containment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Check</strong> your equipment and clothing for live organisms - particularly in areas that are damp or hard to inspect.</td>
<td>Adults and juveniles can be found visually. They could be destroyed by crushing the shells if there are small numbers present. Veligers will not be seen and could only be treated through directed treatment of any water that might be transferred off site.</td>
</tr>
<tr>
<td><strong>Clean</strong> and wash all equipment, footwear and clothing thoroughly. If you do come across any organisms, leave them at the water body where you found them.</td>
<td>This will help to remove veligers and translocated mussels. Washing of equipment in hot water is advisable - 5 minutes at 50 ℃ is suggested. Washing and cleaning will be more of a challenge for established colonies on structures that are to be removed from the waterbody. It is recommended that additional control measures are drawn-up for the movement of structures that have been present in the water for a prolonged period.</td>
</tr>
<tr>
<td><strong>Dry</strong> all equipment and clothing - some species can live for many days in moist conditions. Make sure you don’t transfer water elsewhere.</td>
<td>Drying equipment will be effective at killing veligers. Shelled juveniles and adults may survive for up to 22 days in high humidity and low temperature. Fully drying (i.e. &lt;10% humidity) is recommended for 5 days at room temperature.</td>
</tr>
</tbody>
</table>

The Check, Clean, Dry initiative has proven to be highly effective in limiting the spread of the killer shrimp, Dikerogammarus villosus, through Britain’s waterways. It is also pertinent to review the success of additional measures that have been used to contain the spread of dreissenid mussels.

**Case Study: Biosecurity measures for quagga and zebra mussels in Lake Mead, USA**

In 2002-2003 and 2007-2008, a study was conducted in Lake Mead, USA (Mueting and Gerstenberger 2011). It found that increased awareness of boaters about zebra and quagga mussels did not change cleaning habits of boaters. From 2003 to 2008, the proportion of boaters that were aware of Dreissena spp. significantly rose from 40 to 85%. However, throughout the period the percentage of boaters who cleaned their watercraft between launches remained unchanged at 80 to 85%. In addition, the survey revealed that boaters usually apply cleaning methods that are insufficient in completely removing or killing Dreissena spp.

**Case Study: managing the spread of zebra mussels in the Ebro basin, Spain**

Between 2001 and 2007, 56 boating reservoirs located in the River Ebro basin, Spain, underwent an intervention programme aimed at reducing the spread of zebra mussel populations (Duran and Marco 2008). It found that a range of preventive interventions “helped to prevent the spread of the
zebra mussel (*Dreissena polymorpha)*. However, quantitative data was not provided. The main interventions adopted since 2001 were (1) an advertising campaign informing river users on the mussel’s impacts, pathways and actions that can help prevent its spread; (2) closing access to some infected reservoirs; (3) introducing access controls and disinfection stations at other infected reservoirs. Vehicle inspections and rigorous cleaning was also implemented, inclusive of emptying ballast water and disinfecting critical points such as anchors and motors.
4. Legislation, permits and system-specific constraints

In order to implement a rapid response to quagga mussels it will be necessary to have regulatory approvals for the selected intervention. The necessary approvals will be dependent upon the response involved and the nature of the water body being treated.

Individual waterbodies may be subject to additional regulations. Regulatory approvals can take some time to be granted, and so it is suggested that any short-listed responses for quagga mussel eradication are registered for approval at the earliest possibility, and preferably before quagga mussels are discovered in Britain. Four legislative requirements of the greatest importance are detailed below.

i) EU Biocides Regulation (Regulation 528/2012)

If a chemical treatment is to be used then the product must be approved for use as a biocide under the EU Biocides Regulation. A biocidal product is one which controls harmful or unwanted organisms through chemical or biological means. Importantly, the product may already be permitted for use in freshwaters for other purposes, but if the specific intention is to kill an invasive species then a biocide permit must be held.

The EU Biocides Regulation (Regulation 528/2012)[2] covers a very diverse group of products, including disinfectants, pest control products and preservatives. It repealed and updated the Biocidal Products Directive 98/8/EEC (the BPD ) and the supporting UK Biocidal Products Regulations[3] (BPR) from 1 September 2013.

The Control of Pesticides Regulations[4] (COPR) is an older, UK national scheme which covers various pest control products that contain active substances, which are not yet regulated under BPR. Products controlled under COPR are gradually moving under the scope of the Biocidal Products Regulations, with COPR eventually expected to become redundant.

It is highly likely that a chemical agent selected for quagga mussel treatment will not be listed on the approved products list under the EU Biocides Regulation. As such, a certificate of Notification of Research & Development must be applied for through the Health and Safety Executive (HSE). Supportive information on the product, trial location and quantities to be used must be supplied. The permit requires that data are collected to quantify the efficacy of the trial.

Section 85 of the WRA is concerned with the offence of polluting a controlled waterbody. The purpose of the section is to impose criminal liability on those who pollute natural water resources. The main offence states that it is an offence to cause or knowingly permit poisonous, noxious, or polluting matter to enter any controlled waters.

Under the WRA it will be necessary to have a permit issued by the Environment Agency which will specify the quantity of product that has been permitted for use, and the location of the treated waterway. Documentation will have to be prepared to support the application to the Environment Agency. The Environment Agency must be informed in advance of the dates of the treatment and should be provided with a report at the end of the trial period.

**iii) Natural England permit or Appropriate Agreement**

If any site where intervention is necessary to eliminate the pest species has a statutory designation (SSSI/SAC/SPA/RAMSAR/Natura 2000) then permission must be sought from Natural England to undertake the activity. Timescales for determining applications for consents/assents and permissions are up to 4 months, although in cases where urgent action is necessary Natural England would endeavour to prioritise. For sites with European designations an Appropriate Assessment (for likely significant effect on features of interest) of the proposed activity is normally required and this can be a considerable piece of work.

**iv) Water Supply (Water Quality) Regulations 2000**


If the waterbody in which quagga mussels are discovered is a potable water supply (e.g. a raw water storage reservoir) any chemical intervention must have approval from the DWI. Approved products can be searched at ([http://dwi.defra.gov.uk/drinking-water-products/approved-products/soslistcurrent.pdf](http://dwi.defra.gov.uk/drinking-water-products/approved-products/soslistcurrent.pdf)). Approvals may define a specific limitation to where the product can be applied and what quantity of product can be dosed. This information is contained in the product’s formal Instructions For Use (IFU) document.
Even if a control agent is approved for use under DWI regulations, it must also be acceptable to the water company that abstracts from the waterway. Some chemicals may be incompatible with treatment processes used at a particular works, or control agents may risk the works failing to comply with its permitted water quality standards.

Table 8 summarises the key legislative requirements for any chemical that is selected for use against quagga mussels, along with contact details for each regulatory body and an estimated timeframe to gain consent.

**Table 8. Summary of major permit requirements for using a biocide in GB freshwaters to treat quagga mussels.**

<table>
<thead>
<tr>
<th>Question</th>
<th>Pertinent legislation</th>
<th>Contact point</th>
<th>Timeframe to gain consent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The intervention uses a biocide</td>
<td>Unless the product is listed on the EU Biocides Regulation (Regulation 528/2012) or UK Control of Pesticides Regulations (COPR) it will be necessary to have a Certificate of Notification of Research &amp; Development issued</td>
<td><a href="mailto:Richard.Lomax@hse.gsi.gov.uk">Richard.Lomax@hse.gsi.gov.uk</a></td>
<td>1-2 months, with considerable collation of supporting data</td>
</tr>
<tr>
<td>2. The product will enter the environment</td>
<td>Water Resources Act 1991 (as amended by the Environment Act 1995)</td>
<td>Application will be needed to the Environment Agency. At present the contact would be the Team Leader for Regulatory Water Quality within a particular EA region. Initial contact <a href="mailto:trevor.renals@environment-agency.gov.uk">trevor.renals@environment-agency.gov.uk</a></td>
<td>1-2 weeks with EA support</td>
</tr>
<tr>
<td>3. The site is a potable water supply</td>
<td>Drinking Water Inspectorate Regulation 31</td>
<td><a href="mailto:Sarah.Roberts@defra.gsi.gov.uk">Sarah.Roberts@defra.gsi.gov.uk</a></td>
<td>3-6 months, with considerable collation of supporting data</td>
</tr>
<tr>
<td>4. The site has UK statutory designation</td>
<td>Natural England permit</td>
<td><a href="mailto:Megan.Ellershaw@naturalengland.org.uk">Megan.Ellershaw@naturalengland.org.uk</a></td>
<td>1 week</td>
</tr>
<tr>
<td>5. The site has statutory EU designation</td>
<td>NE Appropriate Agreement</td>
<td><a href="mailto:Megan.Ellershaw@naturalengland.org.uk">Megan.Ellershaw@naturalengland.org.uk</a></td>
<td>3-6 months, with considerable collation of supporting data</td>
</tr>
</tbody>
</table>
5. Recommended rapid responses to quagga mussels in Great Britain

The discovery of the first quagga mussels in Great Britain will require the implementation of a rapid response plan. It is intended that the information collated in this report can allow an appropriate Steering Group to make an informed decision on the best way forward. What is clear is that any chemical-based intervention (i.e. use of a biocide) will require some lead-in time for gaining necessary approvals. Other non-chemical interventions are also likely to require consents and approvals.

It would seem prudent for a Steering Group to review and shortlist the options in advance of quagga mussels being discovered. It may then be possible to collate information necessary to fast-track the necessary permissions. It may also be possible to gain an ‘approval in principle’ if the regulatory authorities are prepared to screen short-listed options in advance.

Clearly the intervention of choice will depend greatly on the nature of the waterbody. The costs will have to be considered both in terms of economics and impact on the wider ecosystem. It is unlikely that the population size of quagga mussels at the point of discovery will affect the intervention chosen because even at low perceived densities there may be many small or undetected individuals (including veligers) that will need to be controlled. As such, the response should aim to control the entire water body, or if employed outside the reproductive season (November to March in Britain) to focus on all hard surfaces onto which mussels can settle.

Based on the tools available, a number of options can be potentially short-listed for use under different scenarios. Before a decision was taken to implement a costly eradication attempt it would be necessary to first confirm with some confidence that the quagga mussels were contained within a clearly defined region. If quagga mussels were found more widely it may still be prudent to implement a scheme to keep the mussel population at a low level as this is likely to reduce the risk of spread to other waterbodies.

1. Small isolated water body

Such a system is the most likely to result in a successful eradication. Dewatering and desiccation would seem the most effective methods, provided the water could be diverted to a sewer and could
not enter the wider environment. Drawdown should last for at least two weeks, and longer if possible. If drawdown was conducted at thermal extremes (i.e. air temperatures < -1.5 °C, or >30°C) then the period of draw-down could be substantially shorter. It is likely that during a draw-down there will remain small pockets of standing water. These could be treated by localised addition of a biocide such as Copper Sulphate at 0.7 mg/l. Such concentrations would not be harmful to the waterbody once it was refilled. During the drawdown process it may be desirable to remove any fish, although there would be a need for a careful quarantine process to ensure that no quagga mussels were transferred elsewhere.

2. Large isolated water body

Draw-down is unlikely to be viable in a large waterbody. The only two methodologies which have achieved 100% eradication in a large water body is the use of potassium chloride at 100 mg/l and copper sulphate at 0.7 mg/l. Of these options, copper sulphate is likely to be the most viable on both a cost and environmental perspective. Experiences at Offlut Base Lake suggest that the copper will precipitate out quickly after treatment, and so the ecosystem would be able to recover after treatment.

Clearly the use of copper sulphate would cause high mortality in non-target biota and may well be unacceptable. Alternative, less damaging control options to consider are presented in scenario 3. Additional options include the use of plastic sheeting to smother the benthos, combined with the addition of a biocide such as copper sulphate beneath the membrane to reduce the overall quantity of product required.

3. Isolated water body used for drinking water

Consultation with the water industry (Barrie Holden, Innovation Manager for Clean Water, Anglian Water) concluded that none of the following biocidal treatments would be acceptable within a potable supply: Sodium hypochlorite at 1.5 mg/l; Chloramine at 1.5 mg/l; Copper sulphate at 0.7 mg/l; Potassium chloride at 100 mg/l; Potassium permanganate at 2 mg/l.

The only approved short-listed biocide that would be appropriate in drinking waters is the use of BioBullets, which has regulatory approval from the DWI, has been demonstrated to be effective in the UK, has previously received consent from the Environment Agency for release into the open environment, and which is relatively specific to mussel control. However, BioBullets have not been used in open water treatments before and so their performance is unknown. Moreover, a 100% kill is unlikely unless the product is used in combination with an additional control agent such as inducing
oxygen stress through the use of plastic sheeting, or through use of combined products such as SB1000 and SB2000. However, costs may be high and preliminary studies may be required to demonstrate viability.

The least environmentally damaging options are also those least likely to offer an eradication, but they may still help to manage the population to a low level. First, hand removal by SCUBA may be possible, but only if the water is sufficiently clear to allow divers to see the mussels. Second, introduction of molluscivorous fishes may help to manage the population. Addition of molluscivorous fishes such as roach (*Rutilus rutilus*) would require preliminary surveys to understand the nature of the existing community, and to estimate the fish biomass. The Environment Agency recommends a fish density of approximately 300 kg/ha for enriched lowland lakes (http://www.environment-agency.gov.uk/static/documents/Business/stocking__eng_172017.pdf), which would be the habitats most likely to support high quagga mussel biomass. To exceed this stocking density might result in undesirable direct and indirect impacts on the ecosystem.

4. **Flowing water (river / stream)**

Flowing water presents considerable challenges because the water cannot typically be contained. Consequently, quagga mussels may have established so far through the system that there are no viable eradication options. Moreover, the costs associated with dosing flowing water with biocides are likely to be much higher because water volumes will be considerably higher.

One possibility is that quagga mussels are found in the lowest reaches of a river, with their downstream distribution constrained by salinity. In such a scenario, salinity change may offer one of the least harmful eradication options in the long term. In a regulated river, this may be readily achieved by reducing downstream flow and therefore allowing the rising tide to bring saline water further upstream. It would be reasonable to expect that any regions of river which can be raised to a salinity of 4 ppt or greater on a daily basis over a protracted period (e.g. 2 months) will be devoid of quagga mussels.

In some smaller rivers and streams it may be possible to dam the affected region and conduct a treatment as if it were a small isolated water body (see 1 above). Quagga mussels will not establish in small streams because the larvae will not survive in shallow water due to the harmful effect of UV radiation. However, they may be found within a canal system, in which case isolation of a section through the use of lock gates may be viable. If a section could be isolated, it is likely that the most effective solution would be draw-down coupled with localised treatment using biocides such as copper sulphate within the standing water (see 1 above).
Local hotspots of quagga mussels could be treated in a river system through smothering with plastic sheeting. However, this would not be effective at achieving an eradication.

5. Brackish water

Quagga mussels are less tolerant of brackish water than are zebra mussels. If quagga mussels were first found in a brackish waterbody it is likely that it would be an isolated water body or the tidal reaches of a river. Appropriate responses for such scenarios are addressed above. The efficacy of the suggested methodologies should not be affected by the low salinities in which quagga mussels occur.

In order to assist with selection of the most appropriate response, Table 9 provides an estimate of the costs, advantages and disadvantages of the more viable control options. The costs are estimates of the product cost, and do not include estimates of surveys, monitoring schemes, staff time, obtaining permits, boats, diving gear etc. However, these additional costs are likely to be similar for most methodologies. For a small waterbody, the selection of treatment agent is unlikely to be affected by price as relatively little product will be required. However, product cost becomes much more important if large areas or volumes of water must be treated. In addition, use of proprietary molluscicides, such as BioBullets, requires a contracted service which may therefore not be directly proportional to the quantity of product used.

The most appropriate methods for delivering the suggested interventions are detailed in the examples and case studies of this report. Generally speaking, biocides should be deployed from a boat using a GPS system to ensure even coverage. Plastic membranes should be installed by divers using weights such as sand bags. In all instances, deployment of interventions should be conducted by individuals with appropriate training, permits, method statements and COSHH forms.
Table 9. Summary of key interventions, estimated costs, advantages and disadvantages.

<table>
<thead>
<tr>
<th>Option</th>
<th>Dosage</th>
<th>Cost</th>
<th>Cost m⁻³</th>
<th>EU BPR Approval?</th>
<th>DWI regs. Approval?</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidising chemicals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elemental chlorine</td>
<td>1.0 mg/l for 40 days</td>
<td>£130/tonne</td>
<td>£0.0052</td>
<td>N</td>
<td>Y</td>
<td>Effective, low cost, rapid degradation</td>
<td>Forms THMs, hazardous to handle, rapid degradation, harmful to non-target biota</td>
</tr>
<tr>
<td>Sodium hypochlorite</td>
<td>1.0 mg/l for 40 days</td>
<td>£260/tonne</td>
<td>£0.0104</td>
<td>N</td>
<td>Y</td>
<td>Effective, safer than chlorine</td>
<td>More expensive than chlorine, forms THMs, costly storage, rapid degradation once dosed, harmful to non-target biota</td>
</tr>
<tr>
<td>Chloramine</td>
<td>1.5 mg/l for 40 days</td>
<td>£2,200/tonne</td>
<td>£0.1320</td>
<td>N</td>
<td>Y</td>
<td>Effective, does not form THMs, persistent, at pH &gt;8.5 as effective as chlorine</td>
<td>Higher doses may be need than chlorine, higher cost, requires premixing on site, harmful to non-target biota</td>
</tr>
<tr>
<td>Chlorine dioxide</td>
<td>1.0 mg/l for 4 days</td>
<td>£1,200/tonne</td>
<td>£0.0048</td>
<td>N</td>
<td>Y</td>
<td>Effective, does not form THMs, relatively persistent, effective at different pHs</td>
<td>Sodium chlorite is an explosion hazard, harmful to non-target biota</td>
</tr>
<tr>
<td>Potassium permanganate</td>
<td>2 mg/l</td>
<td>£750/tonne</td>
<td>£0.0015</td>
<td>N</td>
<td>Y</td>
<td>Effective, does not form THMs</td>
<td>Relatively expensive, fire hazard, difficult to handle, affects water colour, can affect taste and odour, can cause staining, precipitates can clog water treatment systems, harmful to non-target biota</td>
</tr>
<tr>
<td>Non-oxidising chemicals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyelectrolytes</td>
<td>10 mg/l</td>
<td>£5100/tonne</td>
<td>£0.0510</td>
<td>N</td>
<td>Y</td>
<td>Effective, compatible with potable supplies</td>
<td>Expensive, harmful to non-target biota</td>
</tr>
<tr>
<td>Zequanox</td>
<td>100 mg/l</td>
<td>£30,000/tonne</td>
<td>£3.0000</td>
<td>N</td>
<td>N</td>
<td>May be relatively specific</td>
<td>High doses, expensive, no field data available, ecological impacts unknown, not approved for use in UK</td>
</tr>
<tr>
<td>BioBullets (SB2000)</td>
<td>2.5 mg/l</td>
<td>£30,000/tonne</td>
<td>£0.0750</td>
<td>N</td>
<td>Y (SB1000, SB2000)</td>
<td>Effective, specificity to filter feeders, DWI approved, tested by and acceptable to UK water industry</td>
<td>Expensive, some non-target biota may be affected, has not been used in open water</td>
</tr>
<tr>
<td>Product</td>
<td>Concentration</td>
<td>Price/Unit</td>
<td>Price/tonne</td>
<td>EU 1033/2013</td>
<td>Persistent, approved by EU as a biocide, effective case studies</td>
<td>Persistent, DWI allows only 2 mg/l Cu, harmful to non-target biota</td>
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<tr>
<td>Copper sulphate</td>
<td>0.7 mg/l</td>
<td>£1,700/tonne&lt;sup&gt;a&lt;/sup&gt;</td>
<td>£0.0012</td>
<td>Y</td>
<td>Persistent, approved by EU as a biocide, effective case studies</td>
<td>Persistent, DWI allows only 2 mg/l Cu, harmful to non-target biota</td>
<td></td>
</tr>
<tr>
<td>EarthTec</td>
<td>17 mg/l</td>
<td>£5,500/tonne&lt;sup&gt;a&lt;/sup&gt;</td>
<td>£0.0935</td>
<td>N</td>
<td>Effective</td>
<td>Same as for copper sulphate. Expensive, no UK regulatory approval.</td>
<td></td>
</tr>
<tr>
<td>Potassium chloride</td>
<td>100 mg/l</td>
<td>£270/tonne&lt;sup&gt;a&lt;/sup&gt;</td>
<td>£0.0270</td>
<td>N</td>
<td>Effective, case studies available</td>
<td>High doses, persistent for decades, harmful to non-target biota</td>
<td></td>
</tr>
<tr>
<td>pH adjustment to pH 6.5</td>
<td></td>
<td>£120/tonne&lt;sup&gt;l&lt;/sup&gt;</td>
<td></td>
<td>N</td>
<td>Effective, long-term protection against veligers</td>
<td>Persistent, incompatible with some potable water treatments, target pH dependent on calcium hardness, sulphate levels may be high, corrosion, harmful to non-target biota</td>
<td></td>
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<tr>
<td>Non-chemical control</td>
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<tr>
<td>Thermal shock</td>
<td>site specific</td>
<td>site specific</td>
<td>site specific</td>
<td>N/A</td>
<td>N/A</td>
<td>Effective</td>
<td>Viable for cleaning boats &amp; equipment, not viable to large water bodies</td>
</tr>
<tr>
<td>Hand removal</td>
<td>N/A</td>
<td>£2000/day&lt;sup&gt;g&lt;/sup&gt;</td>
<td>site specific</td>
<td>N/A</td>
<td>N/A</td>
<td>Targeted, specific</td>
<td>Expensive, highly unlikely to achieve eradication</td>
</tr>
<tr>
<td>Addition of moluscivores</td>
<td>0.5 m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>£50 per 1000 fish&lt;sup&gt;h&lt;/sup&gt;</td>
<td>£0.0250</td>
<td>N/A</td>
<td>N/A</td>
<td>Relatively targeted, semi-persistent but reversible</td>
<td>Challenging to manage, no case studies, may result in undesirable ecosystem shift</td>
</tr>
<tr>
<td>Desiccation</td>
<td>site specific</td>
<td>site specific</td>
<td>site specific</td>
<td>N/A</td>
<td>N/A</td>
<td>Highly effective, especially if combined with thermal extremes</td>
<td>Disposal of water, risk to infrastructure, loss of potable supplies, harmful to non-target biota</td>
</tr>
</tbody>
</table>

<sup>a</sup> - based on mean values quoted at www.alibaba.com

<sup>b</sup> - assumes a daily dose to maintain a constant chlorine residual

<sup>c</sup> - based on values quoted by SNF Ltd.

<sup>d</sup> - commercial biocides are not sold as a commodity but as part of a bespoke service. Costs are therefore an approximation and prices will be needed on a site-by-site basis

<sup>e</sup> - based on values quoted at www.aquaticeco.com

<sup>f</sup> - based on values for sulphuric acid, www.alibaba.com
\textsuperscript{g} based on assumption of two-man team

\textsuperscript{h} based on UK values given in www.fisheriesmanagement.co.uk, using roach of 10 to 20 cm
6. Suggested action plans

Upon the discovery of quagga mussels in Britain, it will be necessary to mobilise a rapid response quickly and efficiently. Some of the possible responses required are suggested in tables 10 and 11. It is likely that a more refined plan will need to be drawn-up through consultation with key stakeholders. However, it is recommended that an action plan is agreed in advance of the event so that the chances of a successful containment and eradication are maximised.

An action plan will require a cost-benefit analysis, along with an assessment of the likelihood of multiple invasions (or re-invasions). Implementation of an expensive intervention is unlikely to be cost-effective if multiple invasions are likely.

Table 10. Suggested actions required following the discovery of quagga mussels in Great Britain. This table is provided for illustration, and is likely to require refinement by relevant stakeholders.

<table>
<thead>
<tr>
<th>Action</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rapid response Steering Group convened</td>
<td>A rapid response Steering Group should be established in advance of any discovery. Additional stakeholders may need to join. A budget for immediate response should be identified (suggest £30k).</td>
</tr>
<tr>
<td>2. Most appropriate intervention should be identified</td>
<td>A rapid screening of the available options discussed in this report should allow for a selection of the most appropriate response (suggest a budget of £50k).</td>
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<tr>
<td>3. Biosecurity measures should be implemented for the site</td>
<td>Check, clean, dry; engagement with site users; possible short-term closure of access</td>
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<tr>
<td>4. Press release issued</td>
<td>A draft press release should be drawn-up in advance to the event and approved by the Steering Group</td>
</tr>
<tr>
<td>5. Surveys conducted at site</td>
<td>Appropriate contractors identified in advance. May require dredging, hand sampling, ROV, divers. Biosecurity method statements required</td>
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<tr>
<td>7. Design intervention regime</td>
<td>In consultation with contractor and Steering Group</td>
</tr>
<tr>
<td>8. Gain necessary consents for intervention</td>
<td>These will need to be fast-tracked. Consideration should be given to gaining indicative approvals of favoured short-listed interventions prior to discovery.</td>
</tr>
<tr>
<td>9. Design appropriate biomonitoring regime</td>
<td>To include quagga mussels in replicated sample bags, macroinvertebrate and fish surveys, repeat surveys at fixed points post dosing (e.g. Days 1, 7, 28, 56, 6 months)</td>
</tr>
<tr>
<td>10. Treat the invaded waterway</td>
<td>Quantitative data to be collected throughout the management regime, with photographs.</td>
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<tr>
<td>11. Quantify success and engage with stakeholders</td>
<td>Regular meetings of Steering Group and stakeholders</td>
</tr>
<tr>
<td>12. Project debrief</td>
<td>Fully documented response so that experiences can inform on future responses.</td>
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</tbody>
</table>
Table 11. Suggested timetable for actions in a rapid response to the discovery of quagga mussels in Great Britain. This table is provided for illustration, and is likely to require refinement by relevant stakeholders.

<table>
<thead>
<tr>
<th>Action</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
<th>Day 5</th>
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<th>Day 7</th>
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<th>Wk 8</th>
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<tbody>
<tr>
<td>1. Rapid response Steering Group convened</td>
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<td>2. Most appropriate intervention should be identified</td>
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<tr>
<td>3. Biosecurity measures should be implemented for the site</td>
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<td>4. Press release issued</td>
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<td>5. Surveys conducted at site</td>
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<td>6. Surveys conducted in nearby water bodies.</td>
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<td>7. Design intervention regime</td>
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<td>8. Gain necessary consents for intervention</td>
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<td>9. Design appropriate biomonitoring regime</td>
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<tr>
<td>10. Treat the invaded waterway</td>
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<tr>
<td>11. Quantify success and engage with stakeholders</td>
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<tr>
<td>12. Project meetings/debrief</td>
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</tbody>
</table>
We are grateful to the guidance on regulatory matters provided by Barrie Holden (Anglian Water), Nigel Shelton (Natural England) and Richard Lomax (Health & Safety Executive).

The author of this report, Dr David Aldridge, is also Managing Director of BioBullets Limited.
8. References


Britton DK, Dingman S (2011) Use of quaternary ammonium to control the spread of aquatic invasive species by wildland fire equipment. AQUATIC INVASIONS 6, 169-173.


Cameron GN (1989) JOURNAL OF THE AMERICAN WATER WORKS AUTHORITY 10, 53-61


Claxton, WT, Mackie, GL. Seasonal and depth variations in gametogenesis and spawning of Dreissena polymorpha and Dreissena bugensis in eastern Lake Erie. CANADIAN JOURNAL OF ZOOLOGY 76, 2010-2019.

Comeau S, Rainville S, Baldwin W, Austin E, Gerstenberger S, Cross C & Wong H (2011) Susceptibility of quagga mussels (Dreissena rostriformis bugensis) to hot-water sprays as a means of
watercraft decontamination. BIOFOULING 27:267-274.

Connelly NA et al. (2007) Economic impacts of zebra mussels on drinking water treatment and electric power generation facilities. ENVIRONMENTAL MANAGEMENT 40, 105-112.


Lewis DP et al. (1996) Chronic exposure of adult and larval zebra mussels at low level potassium concentrations; laboratory studies. In: Proceedings of the Sixth International Conferences on Zebra Mussels and Other Aquatic Nuisance Species, Dearborn, USA.


Matthews RF, McMahon RF (1995) Survival of zebra mussels (Dreissena polymorpha) and Asian clams (Corbicula fluminea) under extreme hypoxia. Technical Report EL353 to USACE.


Morse JT (2009) Assessing the effects of application time and temperature on the efficacy of hotwater sprays to mitigate fouling by zebra mussels (Dreissena polymorpha Pallas). BIOFOULING 25, 605-610.


Nalepa TF, Fanslow DL, Lang GA (2009) Transformation of the offshore benthic community in Lake Michigan: recent shift from the native amphipod Diporeia spp. to the invasive mussel Dreissena rostriformis bugensis. FRESHWATER BIOLOGY 54, 466-479


Orlova MI, Muirhead JR, Antonov PI et al. (2004) Range expansion of quagga mussels Dreissena rostriformis bugensis in the Volga River and Caspian Sea basin. AQUATIC ECOLOGY 38, 561-573


Sousa R, Pilotto F., Aldridge DC (2011) Fouling of European freshwater bivalves (Unionidae) by the invasive zebra mussel (Dreissena polymorpha) FRESHWATER BIOLOGY 56, 867-876.

Spidle AP, Mills EL, May B (1995) Limits to tolerance of temperature and salinity in the quagga mussel(Dreissena bugensis) and the zebra mussel (Dreissena polymorpha) CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 52, 2108-2119.


Watters A (2011) Effectiveness of EarthTec on killing invasive quagga mussels (Dreissena rostriformis bugensis) and preventing their colonization in the Western U.S. UNLV Thesis


Wright DA et al. (1996) Effect of salinity and temperature on survival and development of young zebra (Dreissena polymorpha) and quagga (Dreissena bugensis) mussels. ESTUARIES AND COASTS 19, 619-628.